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8

THE CONTROL OF THE REACH-TO-GRASP MOVEMENT

Jeroen B. J. Smeets and Eli Brenner

8.1 Kinematics of Reaching to Grasp: Movements of the Digits in Space

The description of how we move when reaching to grasp an object started with the work of Marc Jeannerod (Jeannerod 1981, 1984, 1986). He and many others describe grasping in terms of coordinating the movement of the hand towards the object (i.e., movement of the hand relative to the object) with the pre-shaping and closing of the hand (i.e., movement of the digits relative to each other). In this chapter, we choose a different approach. We focus on the trajectories of the digits relative to the object, and relate them to the sensory information that is used to generate these trajectories. We have discussed at several places why we think this is both a very efficient way of describing grasping and one that is closely related to the way grasping is controlled (Smeets and Brenner 1999, 2016).

In this chapter, we divide the problem of making a reach-to-grasp movement into two phases. First, grasping points on the object are selected. These are the positions at which the digits will make contact with the object's surface. Subsequently, the movement trajectories towards the grasping points are shaped.

We limit ourselves to describing grasping with the finger and thumb, often referred to as a "precision grip." As our description is in terms of individual fingers, one can easily extend it to more than two digits. However, for the selection of grasping points, one has to realize that the thumb often opposes all the other fingers, because the anatomy of the hand often suggests such a configuration. When grasping with more than two digits, one can take this into account and simplify the selection problem by combining the fingers into a single "virtual finger." One can subsequently choose positions for the individual fingers that comply with this virtual finger position (Baud-Bovy and Soechting 2001; Iberall et al. 1986). The digits are then each guided to their chosen positions.

8.2 Selection of Grasping Points

8.2.1 Object Shape and Orientation

When choosing grasping points for the digits, one has to make sure that the object will not slip when one starts to exert grip and lift forces. For this, there are two requirements: the sum of the moments of these vectors should be zero, and each force vector should be within the cone of friction. All combinations of positions of the digits with associated force vectors that fulfill these conditions will lead to a stable grasp. In order to use this grasp to lift the object without it tipping, the line connecting the digits (opposition axis) should pass through or above the object's center of mass. The area on the object that can be used for this is sometimes referred to as opposition space (Iberall et al. 1986; Jeannerod 1999; Stelmach et al. 1994).

If the opposition axis does not pass through or above the center of mass, one can exert torques to prevent the object from rotating. Therefore, subjects usually choose a grasping axis that passes near the center of mass (Lederman and Wing 2003). However, this choice is systematically biased in several ways. For instance, when grasping a 10 cm bar with the right hand, subjects grasp about 5 mm to the right of the center of mass, and when grasping with the left hand, there is a similar bias to the left (Paulun et al. 2014). Visual illusions that influence the perceived location of the center of mass add a bias that corresponds to the effect of the illusion (Ellis et al. 1999).

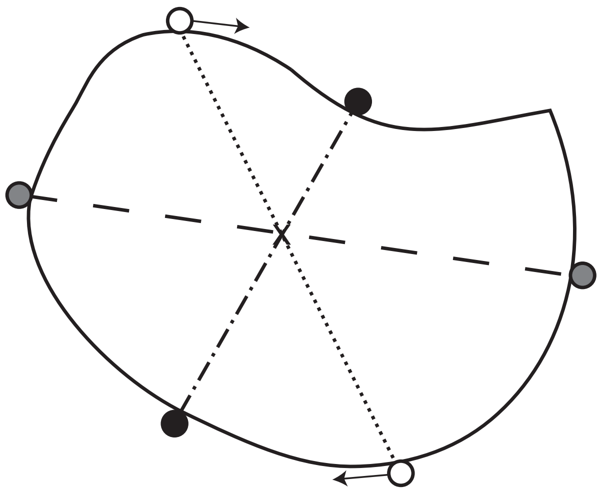

FIGURE 8.1 An object with two possible opposition axes (dashed and dashed-dotted lines), and one set of grasping points (circles connected by dotted line) that will slip in the direction of the arrows if a grip force is applied and the friction is low

For objects with a circular shape, there are an infinite number of opposition axes that are equivalent in terms of opposition space. Nevertheless, subjects have a very clear preference for a certain grip orientation (Rosenbaum et al. 2001; Schot et al. 2010). Such preference has been interpreted in terms of striving for comfort (Cruse et al. 1993). The preferred orientation is presumably based on physical experience, and is therefore based on the anatomy of the arm and hand. When choosing an orientation, one does not actually compare the comfort of the two configurations, but must associate visual information on the opposition axes with memory of earlier experiences using the corresponding postures (Rosenbaum et al. 2001). Although one might think that it is useful to be able to see a grasping point before moving to it, the visibility of grasping points does not affect the choice between possible opposition axes, so apparently the posture is more important (Voudouris et al. 2012a).

When an object is not circular-symmetric, there are generally several possible opposition axes. The various options might differ in their stability. A stable opposition axis allows for more variations in finger placement while leaving the ability to lift the object intact (e.g., the dotted line in Figure 8.1illustrates a more stable opposition axis than does the continuous line). For an elliptical object, there are two stable opposition axes: the principle axes. Grasping along the short axes is more stable than grasping along the long axis. When allowed to choose, subjects do indeed have a preference for the short one. However, this preference is not absolute, as it decreases if the short axis' orientation differs considerably from the anatomically preferred orientation (Cuijpers et al. 2004).

Is this choice of grasping point really made before the movement starts, or does it evolve during the execution of the grasp? One of the findings on grasping elliptical objects is that subjects do not grasp exactly along one of the principle axes of the ellipse, but have a systematic bias. One might interpret this as an indication that the contact points are not fully planned, but that subjects adjust their plan based on the comfort they experience during execution. However, this interpretation is incorrect, because the deviation is already clear early in the movement, so the planned grip is not restricted to one of the principle axes (Cuijpers et al. 2006). One might argue that such a choice must be due to a misperception of spatial properties (i.e., object shape). In a study that explicitly addressed the question of whether movements are planned in advance, subjects had to grasp circular and elliptical objects (Hesse et al. 2008). As mentioned in the previous paragraph, a circular object is normally grasped with the digits in a preferred orientation. Nevertheless, when subjects had viewed an elliptical object more than 2 seconds before viewing the circular target, their grasp angle was clearly influenced by the orientation of the elliptical object, showing that the grip orientation is indeed planned well in advance (Hesse et al. 2008).

When grasping an object along a given opposition axis, there are still two possibilities: the thumb can be positioned at either of the two ends. In anatomical terms, it can be grasped with the lower arm pronated or supinated. Subjects generally have a clear preference for one of the two, depending on the object's orientation, with only a small range of orientations for which both options are equally likely (Stelmach et al. 1994). If the visual information is biased (due to a visual illusion) it is the illusory orientation that determines the choice (Crajé et al. 2008). This suggests that choosing grasping points is based on the same processing of visual information as perceptual judgments. However, two tasks being based on the same processing of visual information does not imply that one should be able to perform both tasks, as they may differ in other aspects. Indeed, there are neurological patients that can perceptually discriminate object shapes without being able to choose adequate grasping points and vice versa (Goodale et al. 1994b).

Thus, the choice of contact points is determined in advance, considering the stability of the grip. However, people do not always choose the most stable grip orientation, because the comfort of the required posture is also considered, as well as other task demands. This is possible because the digits are soft and flexible, so their placement is often not extremely critical, making it possible to trade off grip stability and required grip force against using a comfortable posture and the extent to which dexterity is required.

8.2.2 Influence of the Trajectory

In the previous section, we provided ample evidence that the choice of grasping points is based on visual judgments about the object combined with experience with the comfort of grasping postures. This description of the choice process neglects any influences or constraints on the movement of the hand before it reaches the target. This is clearly an over-simplification. For instance, when grasping a 4 cm diameter cylinder from various starting positions, a small (<20 percent) but systematic dependence of the grasp orientation on the initial orientation of the hand has been found (Hesse and Deubel 2009): the more clockwise the initial hand orientation, the more clockwise the grip when the cylinder was grasped. In addition to the initial orientation of the hand, its initial position also has a small effect on grip orientation (Schot et al. 2010). In these experiments, subjects were shown the target object while their hand was already at the starting position, so those postural parameters were available when selecting grasping points.

Do subjects also take the planned trajectory into account? Voudouris and colleagues devoted several studies to this question. In one study (Voudouris et al. 2012b), obstacles were placed near the trajectories towards the digits' anticipated grasping points. The effect of these obstacles was surprisingly small. A consistent effect on the choice was only found for obstacles that were placed near the thumb. Interestingly, similar small effects on the contact points can be induced when the "obstacles" are actually only images in the background. When grasping a target disk that was placed on a screen displaying the images of four disks surrounding the target (roughly resembling the Ebbinghaus illusion, Figure 8.2), the placement of the digits on the target depended systematically on the locations of the images of the disks (de Grave et al. 2005). It was completely evident that the disks were just images, so the effect of obstacles on grasping might not be guided by an evaluation of the risks of colliding with the obstacles (which was zero for the images), but might rather be based on an automatic visuomotor association between visible structures and path selection.

The movement of the hand on its way to the object does not seem to contribute to the grip orientation when grasping. The grip orientation was unaffected both when the movement of the hand was perturbed during the movement (Grea et al. 2000), and when the digits had to deviate from the planned movement due to obstacles (Voudouris et al. 2010). On the other hand, the planning does take future comfort into account: when picking up a bar in order to place it in a specific orientation elsewhere, the comfort at the moment of placement is more relevant for choosing a grip than the comfort when picking it up (Rosenbaum et al. 1992). A possible reason for this "end-state comfort" effect is that comfort corresponds to being able to perform precisely, and the motor constraints for successfully placing a bar are more severe than for successful grasping (Hughes et al. 2012).

Occasionally, the situation that was considered when selecting the grasping points will have changed by the time the grasping movement starts. If one's task is to grasp the lit object, and suddenly a different object is lit, it is clear that one has to reselect grasping points (Paulignan et al. 1991b). What happens if the changes are more subtle? To investigate this, subjects were asked to grasp a cube that was oriented in a way that made people tend to grasp it along one of the axes, but close to the border with orientations for which they would select the other axis. Once subjects started their reach-to-grasp movement, the cube rotated slightly so that it was now at an orientation for which the other grasping axis would normally be preferred. Although it was possible to stick to the chosen grasping axis, on many trials subjects switched grasping axes at a very short latency: 160 ms (Voudouris et al. 2013). This is in line with the suggestion that the selection of grasping points is an automatic process.

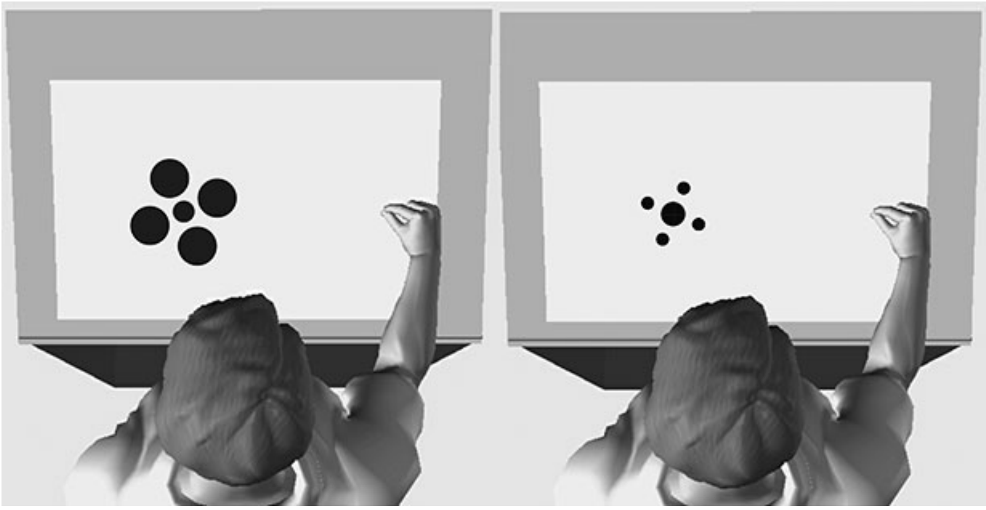

FIGURE 8.2 Grasping the central disk in a configuration resembling the Ebbinghaus illusion (de Grave et al. 2005). The images surrounding the central disk not only make the disk on the right appear larger than that on the left, but also influences the choice of grasping points

Thus, the choice of grasping points can be changed in response to occurrences during the movement, and sometimes depends to a modest extent on the surrounding and on the path towards the object, but the choice appears primarily to depend on the object and the posture of the arm when making contact with it.

8.2.3 Eye Movements

Knowing the eye movements that are made during a task can provide insight into what information is deemed the most interesting at a certain time. As information about the target of a movement is needed before making the movement, knowing where people are looking might reveal how they plan their grasping movements. When grasping objects to place them elsewhere, subjects generally look at a position on the object near where their digit will make contact with it. At least, they do so if subjects can only see one grasping point. They direct their gaze near that point until just before making contact with the object (Johansson et al. 2001).

If both grasping points are visible, many studies report a tendency to look near the grasping point for the index finger rather than the thumb for various types of objects and viewing geometries (Brouwer et al. 2009; Cavina-Pratesi and Hesse 2013; de Grave et al. 2008; Desanghere and Marotta 2011; Voudouris et al. 2016). This tendency is in some way related to grasping, as subjects (initially) direct their gaze to the center of the object during free viewing or when required to make perceptual judgments (Brouwer et al. 2009; Desanghere and Marotta 2011). However, what aspect of grasping causes this tendency is not clear: many hypotheses could be rejected (Voudouris et al. 2016).

If a position on an object is relevant for grasping, and therefore generally fixated, occluding that part of the object does not keep subjects from fixating that location (de Grave et al. 2008). Apparently, the aim of these fixations is not to obtain detailed visual information about the contact position, but rather to obtain extra-retinal information on its location, a conclusion that is in line with the lack of effect of direct visibility on the choice of grasping points that we discussed in section 8.2.4.

8.3 Shaping the Movements

8.3.1 Basic Shape

Once the grasping points are chosen, the digits move towards these points. They do not move along straight paths, but follow curved trajectories so that the digits first move away from the straight line to the grasping point to a position a few centimeters from the object's surface, and then curve towards their grasping points. The points where the trajectories are furthest from a straight line correspond to the maximum grip aperture.

A simple way to model the kinematics of these movements is by finding the smoothest possible movement trajectory that ends at the grasping point with zero velocity and a deceleration perpendicular to the orientation of the surface (Smeets and Brenner 1999). The location of the point at which this trajectory is furthest from a straight line follows directly from the model. When moving to position on a surface, the model predicts that the maximal deviation of the trajectory from a straight line scales with distance from the starting point from a plane through that surface (with a gain of 0.8). In other words: if a grasping point is moved by 1 cm perpendicular to the local surface orientation, the maximal deviation from a straight line will change by 0.8 cm. This is indeed how subjects behave (Smeets and Brenner 2001). When applied to both digits at the same time, the prediction is that maximum grip aperture scales with object size, with a slope of 0.8, again in line with experimentally observed behavior (reviewed by Smeets and Brenner 1999).

Some features of grasping movements are not captured in this simple description. A first one is that maximum grip aperture is not only affected by the distance between the grasping points, but also by other dimensions of the target object. For instance, when grasping an ellipse along its minor axis, the maximum grip aperture is larger than when grasping a circular object with the same size (Cuijpers et al. 2004). A second finding that is not captured by the simple description is that when starting with an open hand to grasp a large object, subjects start by closing the grip and subsequently reopening it (Hesse and Deubel 2009; Meulenbroek et al. 2001; Smeets and Brenner 2002).

By using a dynamics-based model instead of a kinematic one, these additional features of grasping behavior can also be incorporated. In this model, the basic trajectory formation is caused by each digit being attracted towards its grasping point and repelled by other parts of the object (and by other objects), and by assuming that the digits have a preferred distance from each other (Verheij et al. 2012). In this model, the combination of the digits being repelled by other parts of the object and attracted to the grasping points gives rise to curved movements of the digits such that they approach the grasping points more or less perpendicularly (see Figure 8.3). Note that the attracting and repelling forces in this model describe the visuomotor interaction, but they are not directly measurable. This model can be used to make quantitative predictions for hitherto untested situations, such as for the effect of various object shapes on grip formation. Such experiments have been performed and confirmed the predictions to a large extent (Borchers et al. 2014; Verheij et al. 2014a).

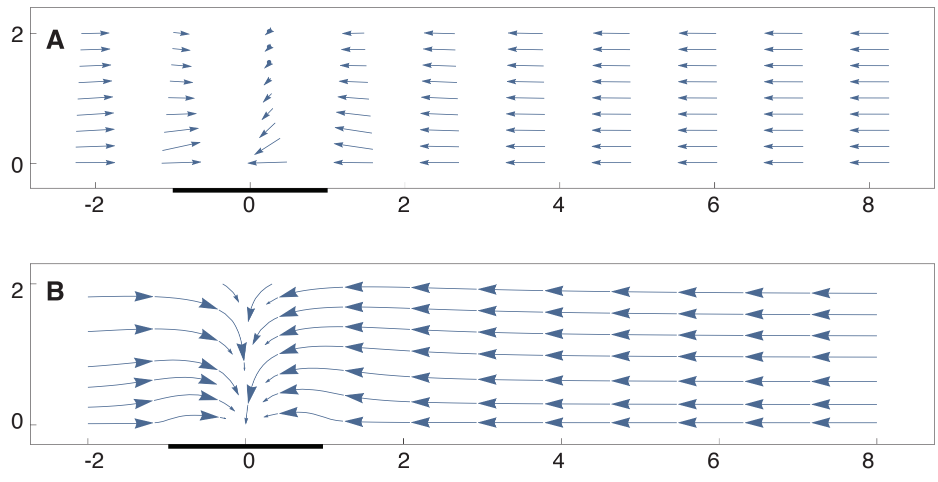

FIGURE 8.3 (A) Example of a force field that is the combination of a repelling force perpendicular to the surface (2 cm wide) and an attractive force towards the grasping point at its center. (B) Possible resulting movement trajectories. This is a caricature of the fields used by Verheij et al. (2012) to model grasping trajectories

Accuracy of grasping is limited by precision of visual localization of the grasping point and proprioceptive localisation of the digits (Smeets and Brenner 2008). However, as the movement is stopped by the grasping surface, the strategy to approach the surface closer to perpendicular can ensure a better precision on the grasping surface (Smeets and Brenner 1999). This is indeed what is observed. Moreover, an equivalent of Fitts' law (Fitts 1954) has also been observed in grasping behavior: the smaller the contact area for the digits, the slower the movement (Zaal and Bootsma 1993).

8.3.2 Individual Differences

Most of the papers discussed in this chapter discuss grasping behavior as a behavior that is common to all humans. A few studies, however, have focused on variations in behavior. For instance, Bongers and colleagues reported that in addition to the gradual opening and closing of the hand that is reported in most studies, sometimes participants open their hand directly to a plateau value, and other trials show a more bumpy behavior (Bongers et al. 2012). Also the timing of opening of the hand and moving of the hand differs: some subjects keep their digits together during the initial part of the movement, and open their hand only during the second half of the movement, whereas others start opening their hand directly at movement onset (Cuijpers et al. 2004).

These variations in movement patterns can be better understood when expressed as the movements of the individual digits through space. If one compares the movement trajectory of the tip of a digit when it is on its way to touch an object with the trajectory of that digit when reaching to grasp the object, they are remarkably similar (Smeets et al. 2010). If one combines a trajectory for the index-finger with one of the thumb, the timing of the pattern of opening and closing is governed by the trajectories of the individual digits. The idiosyncratic grasp formation corresponds to the idiosyncratic differences in the trajectories of the single-digit movements (Smeets and Brenner 2016).

8.3.3 On-Line Control

The stereotypical grasping pattern suggest that these movements are preprogrammed ballistic movements that are executed without peripheral feedback. This is definitely not the case: grasping movements are under visual control. The initial demonstration (Paulignan et al. 1991a, 1991b) showed responses to changing the illumination of objects that did not actually change size or position. The interpretation of these data is that the changes are not on-line adjustments of the movements, but switches to newly planned movements to the alternative target location (Smeets et al. 2002), and thus reselection of grasping points, as discussed in section 8.2.2.

In addition to being able to reprogram movements when the situation changes substantially, one would expect goal-directed movements of the digits in grasping to continuously be adjusted to accommodate improved location information (de Brouwer et al. 2014) or compensate for any movement errors. Consequently, they should follow any changes in the grasping locations that occur during the movement with a very short latency (~100 ms; Smeets et al. 2016), just as the digits do in other goal-directed movements. This is indeed what is found when an object rotates (Desmurget et al. 1996; Voudouris et al. 2013), changes size (van de Kamp et al. 2009; van de Kamp and Zaal 2007) or changes position (Grea et al. 2002). Similar behavior has also been reported for responses to changes in object size in bimanual grasping (Zaal and Bongers 2014).

The responses to a perturbation of the location of a target of a goal-directed hand movement depends on the timing: the later the perturbation during the movement, the more vigorous the response (Liu and Todorov 2007; Oostwoud Wijdenes et al. 2011). Is this also the case in grasping? This has not been investigated directly, but indirect evidence can be found in reported latencies of adjustments. When using a conservative detection threshold to determine a latency, one will find shorter latencies for more vigorous responses (Oostwoud Wijdenes et al. 2014). Responses to perturbations of object size in grasping movements have been reported to have shorter latencies when applied later in the movement (Hesse and Franz 2009; van de Kamp et al. 2009). We propose that this is because they are more vigorous. So the control of grasping is also similar to the control of goal-directed movements of the digits in this respect.

Goal-directed hand movements are not only adjusted when the target is perturbed, but also when feedback about the hand is perturbed (Brenner and Smeets 2003; Franklin and Wolpert 2008). Volcic and Domini (2016) performed a similar experiment in grasping. They changed the feedback of the hand subtly once grip aperture had reached the size of the object. When the hand opened further than the size of the object, the additional finger and thumb movement was either magnified or reduced. Subjects compensated for this manipulation, by moving the digits less far or further apart, respectively. This correction only happened when the viewing geometry allowed subjects to see the distance between their finger and the grasping surface. Thus, altogether, it is evident that grasping movements are under continuous visual control.

8.3.4 Obstacles

The repelling forces in the dynamic model are not only caused by other parts of the object that is grasped, but also by other objects near the grasping trajectory. The obstacles affect both the spatial and temporal aspects of the movement. The temporal effect of an obstacle near the grasping location of a digit is to slow down the grasping movement (Biegstraaten et al. 2003; Mon-Williams et al. 2001; Tresilian 1998; Voudouris et al. 2012b). As grasping with an obstacle near the grasping location requires a more accurate movement, this finding is in line with the well-known speed-accuracy trade-off. It can also be understood in terms of the dynamical model: obstacles correspond to a repelling force, so that the sum of the attracting and repelling force is smaller, leading to a slower movement. The second effect of an obstacle is that it changes the curvature of the digit's path, leading to change in maximum grip aperture. This effect is easy to understand if we consider an obstacle as a repeller, although other model interpretations have also been proposed (Vaughan et al. 2001).

We already mentioned in section 8.2.2 that pictorial elements that could be interpreted as obstacles influence the choice of grasping points (de Grave et al. 2005). Such images that can be interpreted as obstacles also affect the trajectories of the digits towards grasping points: moving images of flankers in the Ebbinghaus illusion closer to the target results in a larger maximum grip aperture (Haffenden et al. 2001). In interpreting this experiment, it is difficult to separate the obstacle effect from the effect of the illusion itself (Kopiske et al. 2016), as will be discussed in section 8.3.6.

The biggest obstacle for our hands in our daily office routines is the table. Does the table indeed influence our movements as an obstacle? One might think so, as our hand movements that start and end on a table curve upwards, away from the table. However, this interpretation is not valid. Verheij and colleagues removed (parts of) the table, and found virtually no effect, provided that the small horizontal surface near the start and the target object ensured an upward start and a target approach from above (Verheij et al. 2013b). An object in between these positions at table height did not affect the curvature. Only objects that were higher than the starting position affected the vertical curvature of the digits during a grasping movement (Verheij et al. 2014b). An additional (minor) cause of the vertical curvature of grasping movements is gravity: this was shown by rotating the participant together with starting position and target relative to gravity. The curvature of the digits paths in the grasping movement was only mildly affected by this manipulation, corresponding to a direct (downward) effect of gravity (Verheij et al. 2013a).

8.3.5 The Moment of Contact

In our description of trajectory formation, the geometry around the grasping point plays an essential role: the digits are not just closing towards the grasping points, but tend to approach the local surface perpendicularly (Smeets and Brenner 1999), which can be interpreted as the surface acting as a repeller

(Verheij et al. 2012). A straightforward way to test this is to vary the orientation of the contact surface while keeping the grasping points constant. If one does so (and makes sure that the edges of the object do not act directly as obstacles), one finds that the trajectories of the digits vary with local surface orientation (Kleinholdermann et al. 2007).

One might expect that both digits will contact the object at the same moment. However, this is not the case. Several studies report that the index finger makes contact tens of millimeters before the thumb (Biegstraaten et al. 2006; Brouwer et al. 2009; Cavina-Pratesi and Hesse 2013; Reilmann et al. 2001; Voudouris et al. 2012a). These studies report that the early arrival of the index finger is associated with a late departure. Such a tendency to synchronize movements of the digits rather than the moment of contact has also been reported for bimanual pointing movements (Boessenkool et al. 1999).

It is well known that haptic (tactile) information is essential for object manipulation: haptic feedback ensures that contact forces are scaled to prevent slip and excessive forces (Johansson and Flanagan 2009). It is less well known that haptic feedback is essential to shape the digits movements in grasping. If one has to pantomime grasping, i.e., perform the action without any haptic feedback, the basic shape of the trajectories and properties such as the scaling with object size are different (Goodale et al. 1994a). If a real object is present, but variations in visual information on object shape are inconsistent with the haptically experienced shape, some subjects neglect the visual information (Cuijpers et al. 2008). The presence of veridical haptic feedback is also essential for a patient with a ventral lesion to be able to normally grasp objects (Schenk 2012).

After contact, the digits start applying forces to the surface in order to provide adequate grip and lift forces to lift the object without it slipping. These lifting forces are not perpendicular to the surface, but directed a bit upward. One might expect that the movement of the digits just before contact is already aligned with this direction, and that variations in the approach direction correspond to variations in initial force direction. This is not the case: the initial contact force is directed downwards (Flanagan et al. 1999) and the direction of approach is not clearly correlated with the initial build-up of force (Biegstraaten et al. 2006). This independence is in line with switching between neural control strategies when transitioning from motion to force production (Venkadesan and Valero-Cuevas 2008). The (relative) timing of the digits' movements and the forces exerted after contact are not accounted for by the above-mentioned models of grasping.

8.3.6 Illusions

Since 1995, the study of grasping objects in an illusory context has become extremely popular. In that year, a paper was published that showed that the Ebbinghaus illusion affected perceptual judgments more than it influenced peak grip aperture in grasping (Aglioti et al. 1995). This result was interpreted by the authors as support for the idea that perception and action are based on two parallel visual processing streams, a ventral one that is susceptible to contextual illusions that underlies perceptual judgments and a dorsal one that neglects the context to control goal-directed movements. Other researches questioned this interpretation (Franz and Gegenfurtner 2008; Smeets and Brenner 2006). A first reason for questioning this interpretation is that the original paper showed that there was an effect of the illusion, so the claim in the title of the paper that the illusion did not deceive the hand is exaggerated. Moreover, as mentioned in section 8.3.4, the discussion as to whether there is an effect of the illusion is confounded with possible interpretations of any differences that are found in terms of obstacles. The second reason is that when appropriately matching the perceptual task to the grasping task, the effects appeared to be equal for both tasks (Franz et al. 2000; Pavani et al. 1999). We won't go further into the specifics of this debate, but refer the reader to other reviews (Schenk et al. 2011; Westwood and Goodale 2011).

Before discussing the third reason, we will discuss an attempt to settle the discussion on whether illusions affect the trajectories in grasping. It has been argued that illusions might affect the planning, but not the execution of the grasping movement, which would then result in a gradual decrease of the effect of illusions such as the Ebbinghaus illusion during the course of the movement (Glover and Dixon 2002). Although the experimental results seem to support this claim, their interpretation is not without pitfalls. In line with the need to precisely equate the tasks that was mentioned in the previous paragraph, one can only draw a definitive conclusion from the time course of the effect of the illusion if one can predict how a constant illusion effect would influence the trajectories of the digits. Doing so predicts that a constant illusion effect results in an illusion effect on the digits' trajectories (and thus grip aperture) that gradually decreases as the movement unfolds (Smeets et al. 2003).

A year after Aglioti et al.'s original publication, their interpretation that actions are immune to illusions was questioned by us (Brenner and Smeets 1996). We showed that the Ponzo illusion (Figure 8.4) did not affect the movements of the digits towards the object, but did affect the forces used to lift the object. The third objection is thus that grip aperture might be immune to the illusion, but motor control is more than opening a hand. As grasping is moving digits to positions, there is no reason to expect an illusion that does not affect positions to influence the trajectories of the digits to these positions.

On the other hand, to lift an object, a visual estimate of weight is required, and size can provide such an estimate (Gordon et al. 1991). The lack of effect of the Ponzo illusion on grip aperture despite a clear effect on lift forces has been replicated and extended to grip force by Jackson and Shaw (2000). Several later studies confirmed the lack of effect of the Ponzo illusion on the trajectory of the digits (Ganel et al. 2008), although one study reported an effect in the first few trials (Whitwell et al. 2016).

The Müller-Lyer illusion has been much more popular than the Ponzo illusion for studying grasping behavior. Most papers reported an effect of the illusion, but its effect on maximum grip aperture when grasping the central bar was much smaller that its perceptual effect. In their extensive review of this literature, Bruno and Franz (2009) argue that two factors might underlie this difference. The first is that one would not expect an equal effect, because (as discussed in section 8.3.1) a 1 cm real change in object size should only lead to a 0.8 cm larger grip aperture. The second is that in grasping you can correct your movements based on visual feedback during the movement. On the other hand, others have argued that the effects might not be due to the illusory size at all, but due to the fins being considered as obstacles that change the precision requirements. An argument for this account is based on the analysis of the trajectories near the moment of contact. If a larger-than-normal peak grip aperture were due to misperception of the bar's size, one would expect a prolonged low velocity phase before contact, as contact would not have been obtained at the expected position. Such a prolonged deceleration phase was not observed (Biegstraaten et al. 2007).

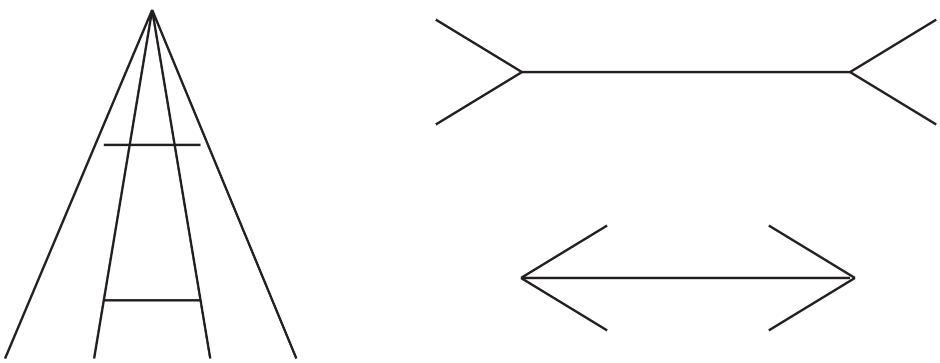

FIGURE 8.4 Two size illusions that have been used in grasping research. In the Ponzo illusion (left) and the Müler-Lyer illusion (right) the two horizontal lines are equally long, but the context lines make the upper line look larger than the lower line

Other illusions were tested to rule out the possibility that movement trajectories are only influenced by illusions because the latter are interpreted as obstacles. Neither the diagonal illusion (Stottinger et al. 2009; Stottinger and Perner 2006) nor the empty space illusion (Stottinger et al. 2012) affected peak grip aperture during grasping. To reconcile all these studies, one could argue that pure *size* illusions do not affect the movements of the digits in grasping (and thus peak grip aperture) because the digits move towards positions. The fact that some illusory figures affect grasping might be due to other effects, such as a misperception of the location of the grasping points or parts of the figures being treated as obstacles.

8.3.7 Moving Targets

Grasping moving targets or catching them has one additional factor which makes the task more complicated than grasping static target: there is no direct visual information about the location of the grasping points to guide your movement. In some way, predictive information has to be used. A seminal study is the experiment by Savelsbergh and colleagues, who studied the timing of the closing movements when catching an approaching ball (Savelsbergh et al. 1991). They manipulated one source of information (optical expansion) by sometimes letting the ball deflate as it approached, and found that subjects delayed their hand closure, as if they expected the ball to arrive later. Other sources of information about (motion in) depth such as binocular disparity and retinal size also play a role in this timing (van der Kamp et al. 1997).

Despite differences between the sources of information and between the way in which the distance between target and hand is reduced (actively in grasping, passively in catching), the timing of events is remarkably similar (van de Kamp et al. 2010). Not only the temporal, but also the spatial aspects of the digits' trajectories are very similar when grasping stationary and moving objects (Schot et al. 2011). This is not a coincidence, but related to the fact that the geometry of the task for the digits is very similar once the hand has started the reach-to-grasp movement: the hand and object are approaching each other, and the digits have to move in such a way that they will approach the object's surface more or less orthogonally.

8.4 Summary

In this chapter, we showed that a close examination of the task geometry can explain how our digits move when we reach out to grasp an object. The laws that govern this behavior are similar to the ones that describe single-digit goal-directed movements. As with any movement, the selection of endpoint depends on why one is making the movement, and the trajectory is under continuous visual guidance, influenced by constraints imposed by obstacles and by the need to be precise.

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